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ABSTRACT

The magnetopause electron layer in the distant magnetotail is an annular region encircling the magnetopause in which bursts of tailward-streaming energetic (E ⩾ 200 keV) electrons are almost continuously present. Sunward-streaming electron bursts with time scales and energy spectral indices similar to those of layer bursts are sometimes observed in interplanetary space upstream of the earth. Evidence is presented to show that the layer bursts and the interplanetary bursts have a common source. With the aid of a new coordinate system--geocentric interplanetary medium (GIPM) coordinates--appropriate for describing the access of energetic charged particles in the inner magnetosheath to a spacecraft located in interplanetary space, it is shown that the interplanetary bursts occur predominantly on the sunward extension of the field lines associated with the magnetopause electron layer.

1. INTRODUCTION

Several investigators have reported observing a layer of energetic electrons adjacent to the dayside and polar magnetopause (Refs. 1-4). Recently Baker and Stone (Refs. 5-7) described the characteristics of a layer just outside the magnetopause in the distant ($X_{GSE} \sim -35\ R_E$) magnetosheath in which bursts of tailward-streaming energetic electrons (E ⩾ 200 keV) are almost continuously present. They showed that, except for a small segment of the high-latitude tail where no data were available due to Imp-8's orbit, the layer encircles the magnetotail. Since the electrons in the layer are streaming along field lines external to the magnetosphere, it might be expected that sunward-streaming electrons can be observed in interplanetary space on the sunward extension of the field lines passing through the magnetopause layer. The present study traces the electron bursts from the layer, through the magnetosheath, and into interplanetary space during one specific passage of Imp-8 through the dawn magnetosheath and bow shock. Bursts of electrons observed in the upstream solar wind are sometimes attributed to acceleration at the bow shock (Refs. 8-10). However, the bow shock spike electrons have somewhat lower energies than the electrons studied here, and they may represent a different phenomenon. Finally, a statistical study of bursts outside the dawn bow shock based on 21 Imp-8 orbits is made. With the aid of a new coordinate system, it is shown that a predominant factor in determining when bursts are observed is the distance from the earth to the extension of the interplanetary field line on which the spacecraft is located. The greatest burst intensity is observed on field lines that trace back to the magnetopause electron layer.

In this study, magnetopause and bow shock crossings were identified with the aid of plasma analyzer data (Ref. 11) and magnetic field data (Ref. 12) acquired simultaneously with the energetic electron data.

2. ELECTRON BURSTS IN THE MAGNETOSHEATH AND OUTSIDE THE DAWN BOW SHOCK

Figure 1 is a plot as a function of time of 8.2-minute averages of the intensity of ⩾ 200 keV electrons observed by Imp-8 during a passage through the dawn magnetosheath and bow shock in 1975. An apparent small, steady background flux of $\sim 10^{-1}\ (cm^2\text{-}s\text{-}sr)^{-1}$ is due to contamination of the data by energetic protons. Also shown in Figure 1 is a plot of Imp-8's trajectory in the X-Y and Y-Z planes of the GSM coordinate system. Bursts of electrons are observed beginning at 0400 on Day 206, which coincides with passage of the spacecraft through the magnetopause, and they continue throughout the magnetosheath. For the magnetopause layer crossing shown, the time scale of the bursts was 120 s. Typical values for other layer crossings ranged from 60 to 300 s.

Imp-8 crossed the bow shock at 0430 on Day 207, and electron bursts of a similar character to the layer bursts continued to be observed in the interplanetary medium. The period of particularly intense bursting from 0600 to 0900 on Day 207 was analyzed in detail, and the bursts were found to have a time scale of 150 s, comparable to the time scale of layer bursts. Although the data are not presented here, a power law energy spectral index of -3.4 was determined for the differential electron flux during this time period, comparable to the value of -3.8 determined for the bursts inside the magnetosheath.

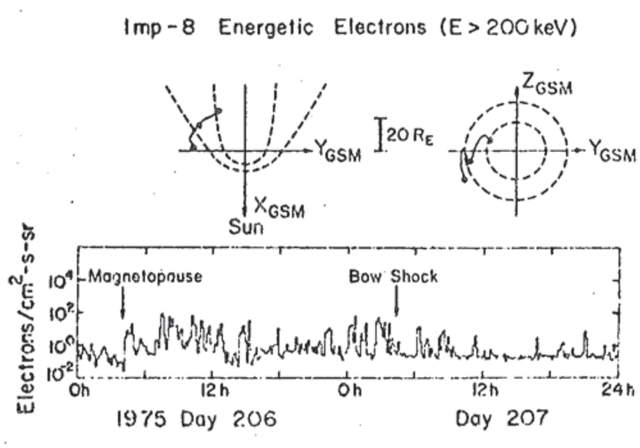

Figure 1. Energetic electron flux during a passage through the dawn magnetosheath and bow shock. The spacecraft trajectory is shown with 24-hour tick marks.

That the time scales and energy spectral indices of layer bursts and interplanetary bursts are similar suggests that the energetic electrons observed in the magnetopause electron layer and in interplanetary space have a common source. This interpretation is supported by the streaming data presented in Figure 2 for the same time period covered by Figure 1. The net streaming vector for each one-hour interval was plotted at the spacecraft location provided that the streaming was statistically significant at the 99 % confidence level. As Figure 2 shows, inside the magnetosphere no streaming at this confidence level was observed. As soon as the spacecraft crossed the magnetopause, tailward streaming of from 3 to 30 % parallel to the magnetopause was observed. As Imp-8 progressed through the magnetosheath, the streaming direction became more variable, but tended to shift away from the magnetopause towards the bow shock. After the bow shock was crossed, strong sunward streaming away from the bow shock along the interplanetary field lines was generally observed.

These data may be interpreted in terms of the schematic representation of magnetosheath field lines presented in Figure 3 for the case of an interplanetary field which has no Z_{GSM} component and which makes an angle of 20^{o} with the Y_{GSM} axis. The magnetosheath field lines adjacent to the magnetopause are essentially parallel to the magnetopause, but as distance from the magnetopause increases, the field lines flare out toward the bow shock, then change discontinuously to the interplanetary direction at the bow shock. For the interplanetary direction shown, which was chosen to be representative of the streaming direction observed in the interplanetary medium, the field lines are deflected inward towards the nose of the magnetopause at the bow shock. For a more typical interplanetary field which makes an angle of $\sim 45^{o}$ with the Y-axis, the field lines would initially be deflected back towards the tail at the bow shock, then gradually turn inward towards the nose of the magnetosphere. Although the details of the magnetosheath field configuration may change, the topology does not. Even though the data of Figure 2 were collected over a two-day period, during which time the interplanetary and magnetosheath fields fluctuated by large amounts, the general streaming pattern supports the interpretation that the sunward-streaming interplanetary electrons have the same source as the magnetopause layer electrons and that they appear in interplanetary space after streaming along field lines qualitatively like those in Figure 3.

3. GIPM COORDINATES

The electron bursts in interplanetary space tend to occur far more infrequently and sporadically than those observed adjacent to the magnetopause. One reason for this is that normally the interplanetary bursts can be observed only when there is a favorable connection between the spacecraft and the source region along the interplanetary field lines. To quantify this geometric effect, a new coordinate system, called geocentric interplanetary medium (GIPM) coordinates, is defined which is more convenient for mapping interplanetary field lines into the magnetosheath than more commonly used coordinate systems such as GSE and GSM.

The motivation for defining GIPM coordinates is illustrated in Figure 4. This shows a spacecraft located in the $X_{GSE} = 0$ plane with two possible configurations of the interplanetary field. For illustrative purposes it is assumed that the X_{GSE} component of the field is zero. On the left

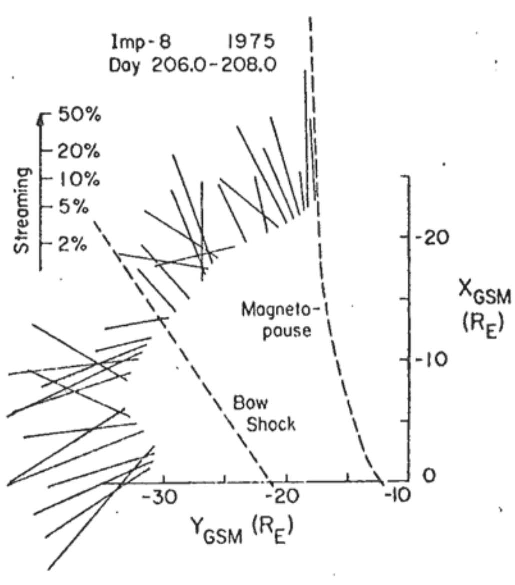

Figure 2. One-hour averages of electron streaming during the same time period shown in the previous figure.

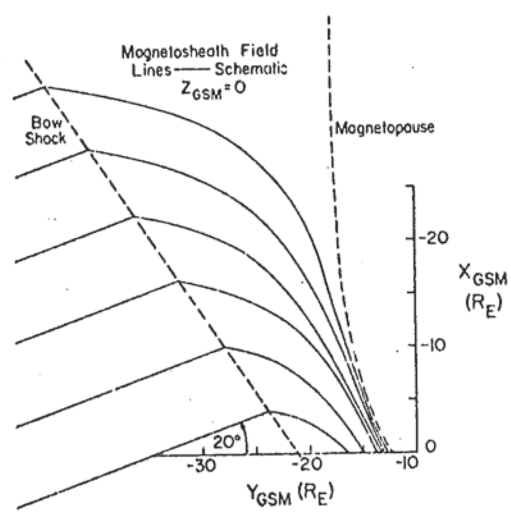

Figure 3. Magnetosheath field lines in the X_{GSM}-Y_{GSM} plane for an interplanetary field with no Z_{GSM} component.

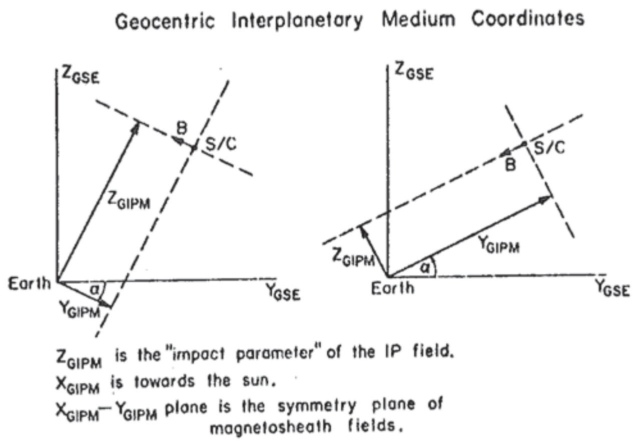

Figure 4. The direction of the interplanetary field controls how deeply a spacecraft can probe into the earth's magnetic environment.

the field points above the horizontal, and, assuming the interplanetary field is constant over the length scale of interest, the closest the magnetic field line through the spacecraft passes to the earth is the distance labelled Z_{GIPM}. On the right the field points below the horizontal, and in this case the distance of closest approach --the impact parameter of the interplanetary field--is a much smaller distance Z_{GIPM}. Therefore the spacecraft can observe particles originating from a point much deeper in the earth's magnetosheath in the second configuration. The GIPM coordinate system is defined so that the Z-coordinate is the impact parameter illustrated in Figure 4. In the general case where $B_X \neq 0$, Z_{GIPM} is the impact parameter of that plane parallel to the earth-sun line which contains both the spacecraft and the field vector $\underset{\sim}{B}$. In this case the field azimuth also plays a role in determining whether the spacecraft is favorably connected to the earth.

In practice, the GIPM coordinate system is defined by rotating the Y_{GSE} and Z_{GSE} axes about the X_{GSE} axis by an angle α such that the Z-component of the interplanetary field vanishes in the new coordinate system. If (B_X, B_Y, B_Z) are the components of the interplanetary field in the GSE system, then the transformation to GIPM coordinates is

$$X_{GIPM} = X_{GSE} \tag{1}$$

$$Y_{GIPM} = Y_{GSE} \cos\alpha + Z_{GSE} \sin\alpha \tag{2}$$

$$Z_{GIPM} = -Y_{GSE} \sin\alpha + Z_{GSE} \cos\alpha \tag{3}$$

where

$$\alpha = \begin{cases} \tan^{-1}(B_Z/B_Y) + 180^\circ & \text{if } B_X B_Y \geq 0 \\ \tan^{-1}(B_Z/B_Y) & \text{if } B_X B_Y < 0. \end{cases} \tag{4}$$

Equation 4 is valid when B_Y is nonzero. If $B_Y = 0$, then $\alpha = 270^\circ$ if $B_X B_Z \geq 0$ and $\alpha = 90^\circ$ if $B_X B_Z < 0$. The definition of α is rather complicated because there are two possible rotation angles separated by 180° which make the Z component of the field vanish. The definition given in equation 4 singles out the one that makes the interplanetary field azimuth measured in GIPM coordinates lie either between 90° and 180° or between 270° and 360°.

Finally, it should be noted that although the above discussion takes no account of the change in the field lines after passing through the bow shock, the property that the interplanetary field lines which probe most deeply into the magnetosheath are those with the smallest values of Z_{GIPM} is preserved in models which do take account of the magnetosheath field. In such models, the X_{GIPM}-Y_{GIPM} plane is the symmetry plane of the solar wind interaction with the earth. Interplanetary field lines with $Z_{GIPM} = 0$ are convected directly towards the earth by the solar wind, and they experience the greatest amount of distortion in the magnetosheath. Field lines with $Z_{GIPM} > 0$ ultimately slip up over the top of the magnetosphere, and those with $Z_{GIPM} < 0$ slip below it, as illustrated graphically in Alksne (Ref. 13).

4. DEPENDENCE OF INTERPLANETARY BURSTS ON FIELD GEOMETRY

The dependence of energetic electron bursts in interplanetary space on field geometry is illustrated in Figures 5 through 7. The base data set for these figures is a set of nearly 60,000 82-s time intervals collected during 21 passages of Imp-8 from the dawn bow shock to the X_{GSM}-Z_{GSM} plane in 1975. In Figure 5 is plotted the spacecraft location in the Y_{GIPM}-Z_{GIPM} plane at 40-minute intervals. This graph shows that Imp-8 has roughly equal access to all points inside the circular region defined by $(Y^2_{GIPM} + Z^2_{GIPM})^{1/2} \leqslant 40\ R_E$.

In Figure 6 is plotted the spacecraft location during those 1062 time intervals when the flux of $\geqslant$ 200 keV electrons was larger than $1\ (cm^2\text{-}s\text{-}sr)^{-1}$. A strong concentration of points near the $Z_{GIPM} = 0$ plane and at large negative values of Y_{GIPM} is immediately evident, and comparison with Figure 5 reveals that this concentration of electron bursts is a real effect, not due to the spacecraft orbit. Note that the projections of the interplanetary field lines in the Y_{GIPM}-Z_{GIPM} plane are horizontal lines. Although it is not obvious in Figure 6, the density of bursts actually is largest at $Z_{GIPM} = 0$ and decreases monotonically away from this plane. Often a series of bursts occurs within a relatively short time, say one hour, during which the spacecraft distance from the earth changes by only a small amount. However, because the $(B_Z)_{GSE}$ component of the interplanetary field can vary significantly on a time scale of ~ 20 minutes, the Y_{GIPM} and Z_{GIPM} distances as defined in Figure 4 can vary over a large range. Such a series of bursts will trace out an arc in the Y_{GIPM}-Z_{GIPM} plane, and several such arcs can be discerned in Figure 6.

The concentration of points near $Z_{GIPM} = 0$ provides additional support to the idea that the interplanetary electrons are related to those in the magnetopause electron layer. According to the steady-state theory of magnetosheath fields (Ref. 13), the field lines closest to the magnetopause connect to interplanetary field lines that have small values of Z_{GIPM}. Therefore the concentration near $Z_{GIPM} = 0$ simply reflects the fact that energetic electrons are most commonly observed when the spacecraft is located on field lines that trace back to the magnetopause layer. The thickness ΔZ_{GIPM} of the region in which electron bursts are observed is ~ 30 R_E, which is about as large as the typical magnetopause cross-section shown in Figure 6. Those points in Figure 6 which lie inside this typical ($X_{GSE} = 0$) cross-section actually represent observations made at large values of X_{GSE}, well out in front of the magnetopause and bow shock. Finally, the strong concentration of bursts evident at large negative values of Y_{GIPM} suggests that at some times a portion of the flow of electrons across the bow shock occurs tailward of Imp-8 in regions not accessible to the spacecraft.

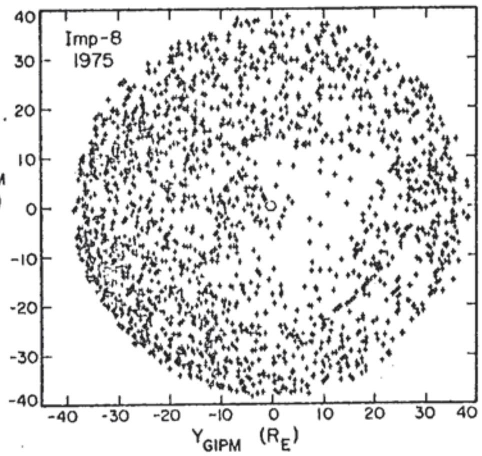

Figure 5. The position of Imp-8 in interplanetary space is plotted at 40-minute intervals for the data set described in Section 4.

The conclusions drawn above are supported by Figure 7, which shows the interplanetary field direction plotted at the spacecraft location in the X_{GIPM}-Y_{GIPM} plane during those 372 time intervals when electron fluxes larger than $10^{1/2}$ $(cm^2\text{-}s\text{-}sr)^{-1}$ were observed. This figure indicates that interplanetary bursts are most commonly observed when the interplanetary field line intersects the bow shock at some point tailward of the earth. For a given interplanetary field direction, bursts are observed over a ~ 42° portion of the spacecraft orbit, which corresponds to an arc length of ~ 26 R_E. This length combined with the 30 R_E thickness in the Z_{GIPM} direction defines an area of ~ 780 R_E^2 in the GIPM coordinate system in which the interplanetary bursts are observed. By comparison, the average cross-sectional area of the magnetopause electron

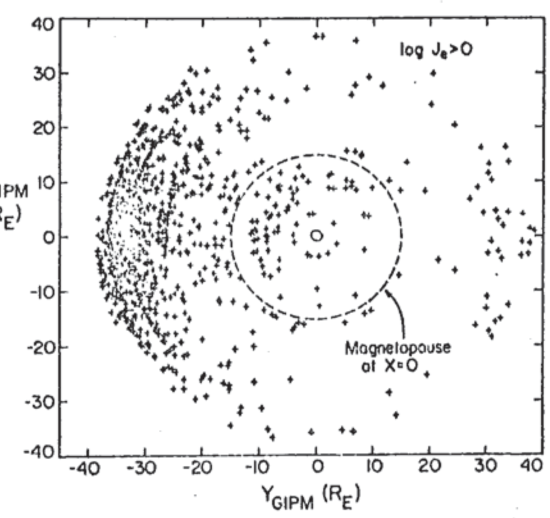

Figure 6. Locations at which electron fluxes of more than 1 $(cm^2\text{-}s\text{-}sr)^{-1}$ were observed in 1975.

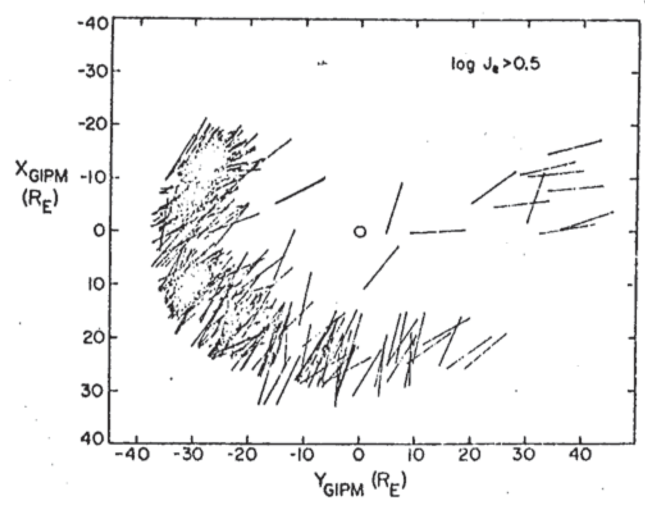

Figure 7. Interplanetary magnetic field direction at locations at which electron fluxes of more than $10^{1/2}$ $(cm^2\text{-}s\text{-}sr)^{-1}$ were observed in 1975.

layer is ~ 430 R_E^2 (Ref. 7). Because the magnetosheath field in the distant tail is ~ 1.7 times stronger than the interplanetary field (Ref. 14), magnetic flux conservation requires that the field lines comprising the layer encompass a somewhat larger area in interplanetary space than the layer area, as is observed. This provides additional evidence that the field lines on which the interplanetary bursts are observed are the sunward extension of the field lines associated with the magnetopause electron layer.

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